(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 427 220 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
09.06.2004 Bulletin 2004/24

(51) Int Cl.7: H04N 9/31

(21) Application number: 03078440.9

(22) Date of filing: 03.11.2003

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IT LI LU MC NL PT RO SE SI SK TR
Designated Extension States:
AL LT LV MK

(30) Priority: 13.11.2002 US 425896 P
24.03.2003 US 395678

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(54) Projection display apparatus having both incoherent and laser light sources

(57) A color display apparatus for forming, on a display surface, a color image of superimposed color images, the display apparatus having a first color modulation channel for forming a first color two-dimensional image using a laser light source for providing a first color source beam, a linear spatial light modulator for modulating the first color source beam, and a scanning element for scanning the modulated light beam to form a first color two-dimensional image. A second color modulation channel forms a second color two-dimensional image using an incoherent light source for providing a second color source beam to an area spatial light modulator for modulating the second color source beam to form a second color two-dimensional image. A projection lens then projects a superimposed color image of the first color two-dimensional image and the second color two-dimensional image and any third color two-dimensional image.

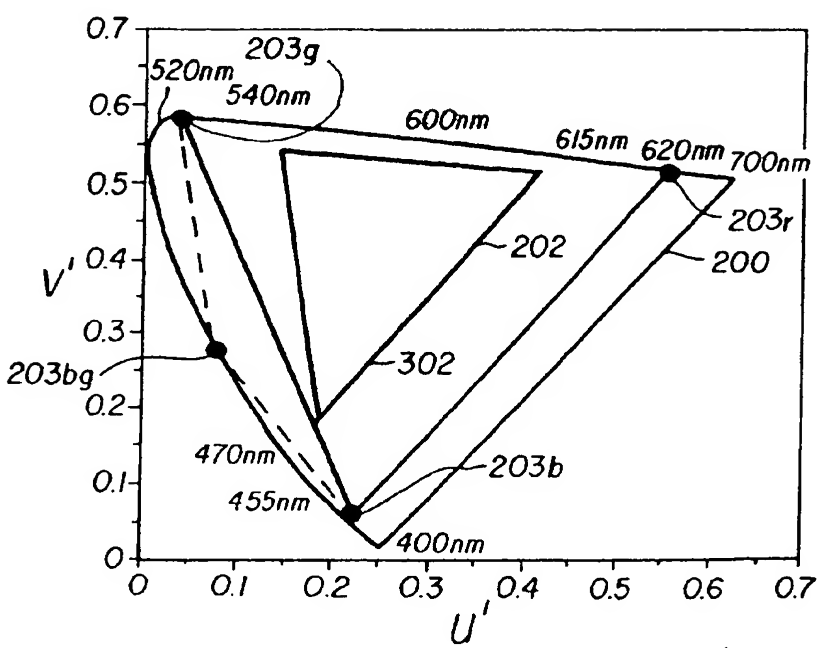

FIG. 7

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CRT-based projection systems. Color gamut is most readily visualized using the familiar tristimulus CIE color model developed by Commission Internationale de l'Eclairage (International Commission on Illumination), which shows the color space perceived by a standard human observer. Fig. 1 a shows the CIE color model, which represents a visible gamut 200 as a familiar "horseshoe" curve. Pure, saturated spectral colors are mapped to the "horseshoe" shaped periphery of visible gamut 200. The interior of the "horseshoe" then contains all mappings of mixtures of colors, including mixtures of pure colors with white, such as spectral red with added white, which becomes pink, for example. Within visible gamut 200, a device gamut 202 is typically represented by a triangle, with vertices approaching the curve of visible gamut 200. In Fig. 1a, device gamut 202, as drawn, approximates the familiar gamut for standard SMPTE (Society of Motion Picture and Television Engineers) phosphors, for example.

[0008] As is well known in the color projection arts, it is desirable for a display device to provide as much of visible gamut 200 as possible in order to faithfully represent the actual color of an image and to provide vivid colors. The component colors of a display, typically Red, Green, and Blue (RGB) define the vertices of the polygon for device gamut 202, thereby defining the area and shape of device gamut 202.

[0009] One basic strategy, then, to increase the size of device gamut 202 is to use light sources that are spectrally pure, or have at least a high degree of spectral purity. Lasers, due to their inherent spectral purity, are particularly advantaged for maximizing device gamut 202. Substantially monochromatic, laser sources effectively position vertices of device gamut 202 onto the periphery of visible gamut 200.

[0010] A number of digital projector designs have been proposed for taking advantage of the favorable spectral qualities of laser sources. For example, U.S. Patent No. 6,183,092 by Troyer, issued Feb. 6, 2001, titled "Laser Projection Apparatus With Liquid-Crystal Light Valves And Scanning Reading Beam," U.S. Patent No. 6,426,781 by Lee, issued Jul. 30, 2002, titled "Laser Video Projector," U.S. Patent No. 6,435,682 by Kaelin et al., issued Aug. 20, 2002, titled "Laser Imaging Using A Spatial Light Modulator," and U.S. Patent No. 6,317,170 by Hwang et al., issued Nov. 13, 2001, titled "Large Screen Compact Image Projection apparatus Using A Hybrid Video Laser Color Mixer" show just a few of the proposed approaches for digital projection using laser illumination sources. Designs such as those disclosed in the patents just listed take advantage of continuing advances in laser design and fabrication that provide increased power, improved lifetimes, and overall lower cost for laser illumination solutions.

[0011] However, in spite of significant advances, the lack of low-cost lasers in the visible blue spectrum remains a problem. Laser manufacturers have, as yet, been unable to provide blue lasers at reasonable cost in the power range needed for digital projection. In fact, the cost of lasers available in the visible blue spectrum can be as much as ten times the cost of green lasers at the needed power levels. To a somewhat lesser extent, the problem of cost and availability also affects red lasers in some power ranges, particularly those providing illumination for large screen projection. This problem, then, dramatically impacts the cost of a projection apparatus, making laser projection an unlikely near-term alternative for wide acceptance with projection systems.

[0012] While lasers provide light that is spectrally pure and therefore allow an enlarged color gamut, there are other characteristics of laser light that are less than favorable for digital projection. Notably, laser light is at least relatively coherent and can be highly coherent. As a result, speckle and other effects are a problem for digital projection devices using laser illumination. As is noted above, area spatial light modulators, particularly transmissive and reflective LCDs, although they perform well with conventional incoherent light sources, such as lamps and LEDs, are not well-suited for modulation of laser light. Instead, linear spatial light modulators, such as GLV and GEMS devices are preferred for use with laser illumination.

[0013] In general, incoherent light sources are not as constrained as are lasers with respect to blue wavelengths. For example, mercury arc lamps, widely available at the necessary power range for projection, radiate light in the visible blue range. In fact, the standard 436 nm line of mercury arc lamps provides a characteristic blue spectral component that is sharply defined. This allows a filter to be used to isolate and pass only this visible blue component. Thus, the mercury arc lamp can serve as an incoherent light source, providing light that is substantially spectrally pure, within the range of wavelengths that are not affordably achievable using lasers.

[0014] LEDs, while not as spectrally pure nor as bright as lasers, provide yet another possible low-cost incoherent illumination source for digital projection systems with small screens. LEDs can provide favorable solutions for some types of display apparatus, particularly since these devices are becoming more widely available at the needed wavelengths.

[0015] It is worthwhile to summarize these considerations for illumination sources in digital projection apparatus design:

(a) lasers, providing optimal color gamut and high brightness, work best with linear SLMs to provide high resolution, but may not currently be affordable at all needed wavelengths, particularly in the visible blue region;

(b) incoherent light sources, such as lamp and LED light sources, may not provide as broad a color gamut as lasers at comparable wavelengths. Incoherent light sources work best with area SLMs used at relatively lower resolution, and are available at wavelengths across the visible spectrum, where la-

(b1) means for providing a second color incoherent source beam;
(b2) means for modulating said second color incoherent source beam to provide a second color image beam to said color combiner;

(c) said color combiner combining at least said scanned line image beam and said second color image beam to form a superimposed color image beam;
(d) means for projecting said superimposed color image beam toward the display surface.

[0022] A third aspect of the present invention provides a method for forming, on a display surface, a color image as a plurality of superimposed images, including the steps of:

(a) forming a first color linear image beam including the steps of:

(a1) providing a first color laser source beam;
(a2) modulating said first color laser source beam to provide at least one diffracted light beam having a first color;

(b) forming a second color two-dimensional image beam including the steps of:

(b1) providing a second color source beam from an incoherent light source;
(b2) modulating said second color source beam;

(c) combining said first color linear image beam with said second color two-dimensional image beam to form a superimposed image beam; and
(d) projecting said superimposed image beam toward the display surface.

[0023] A feature of the present invention is the use of a combination of different types of illumination sources and different types of spatial light modulators within the same display apparatus.

[0024] It is an advantage of the present invention that it obviates the need for obtaining lasers at specific wavelengths in the visible region, particularly in the blue region. The present invention provides methods for using incoherent light sources as well as laser sources.

[0025] It is a further advantage of the present invention that it allows a display apparatus to use lasers on any number of color channels, where lasers are the most suitable and economical, for example, and to use other light sources where they can be most advantageous.

[0026] These and other features and advantages of the present invention will become apparent to those skilled in the art upon a reading of the following detailed description when taken in conjunction with the drawings wherein there is shown and described an illustrative embodiment of the invention.

[0027] While the specification concludes with claims particularly pointing out and distinctly claiming the subject matter of the present invention, it is believed that the invention will be better understood from the following description when taken in conjunction with the accompanying drawings, wherein:

Figure 1 is a graph showing the relationship of the standard SMPTE color gamut to the visible color gamut;
Figure 2 is a schematic block diagram showing the overall arrangement of image modulation components in a display apparatus of the present invention;
Figure 3a is a detailed schematic block diagram showing a first embodiment of a display apparatus using a combination of different types of modulation components, wherein the blue modulation path utilizes a reflective LCD spatial light modulator;
Figure 3b is a detailed schematic block diagram showing an alternate embodiment of a display apparatus using a combination of different types of modulation components, wherein the blue modulation path utilizes a transmissive LCD spatial light modulator;
Figure 3c is a detailed schematic block diagram showing an alternate embodiment of a display apparatus, wherein the blue modulation path utilizes a transmissive LCD spatial light modulator and a second modulation path utilizes a GEMS linear spatial light modulator to provide the two other colors in sequence, from laser sources;
Figure 3d is a detailed schematic block diagram showing an alternate embodiment of a display apparatus, wherein the blue modulation path utilizes a transmissive area spatial light modulator and a second modulation path utilizes two GEMS linear spatial light modulators, fabricated on the same substrate as a single component, to provide the two other colors, with illumination from laser sources having different spatial displacement;
Figure 3e is a detailed schematic block diagram showing an alternate embodiment of a display apparatus for expanded color gamut, wherein the blue modulation path utilizes a transmissive LCD spatial light modulator and a second modulation path utilizes three or more other lasers providing source illumination to GEMS linear spatial light modulators;
Figure 3f is a detailed schematic block diagram showing an alternate embodiment of a display apparatus wherein one color modulation path employs an emissive display device and a second modulation path uses linear spatial light modulators to provide the other two colors from laser sources;
Figure 4 is a detailed schematic block diagram

from dichroic combiner 94 is then directed by a lens 75, through an optional cross-order filter 110, to a scanning mirror 77. Turning mirror 82 acts as an obstructing element for the zeroeth order reflected light from electromechanical grating light modulator 85r.

[0035] As scanning mirror 77 rotates, individual modulated line images from electromechanical grating light modulator 85r, directed through a scan lens 84 and to an optional moving diffuser 86 (for speckle compensation), are provided to a dichroic combiner 92. Dichroic combiner 92 then directs the modulated line images from scanning mirror 77 along output axis O to projection lens 300, which projects the image onto a display surface 90. An optical compensation element 89 may be disposed in the path of red and green modulated light, when necessary, to make the red/green and blue light paths similar for projection lens 300, thereby reducing image aberrations. It should be noted that the scanned line images from green and red color modulation channels 30g and 30r, respectively, are perceived by a viewer as two-dimensional images when the scan refresh rate is sufficiently high, typically at least 48 Hz.

[0036] The path of modulated light from green color modulation channel 30g is similar to the path for red modulated light, just described. Dichroic combiner 94 combines the red and green modulated light and directs the combined light toward scanning mirror 77.

[0037] Still referring to Fig. 3a, the operation of blue color modulation channel 30b differs from that described for red and green color modulation channels 30r and 30g. Incoherent light from light source 22b is filtered at blue-pass filter 24b and polarized at optional polarizer 34, then directed by a lens 76 to a polarizing beamsplitter 93. Polarizing beamsplitter 93 directs light having the proper polarization through an optional quarter-wave plate 42 and to spatial light modulator 32b. Unlike linear spatial light modulators 32r and 32g, spatial light modulator 32b for blue color modulation channel 30b is an area spatial light modulator, a reflective LCD in the embodiment shown in Fig. 3 a. Modulated light from spatial light modulator 32b is then transmitted through polarizing beamsplitter 93 and to dichroic combiner 92, which combines the blue modulated light with red and green modulated light for projection. It is instructive to note that spatial light modulator 32b could alternately be a transmissive LCD, a DMD, or some other type of area spatial light modulator, with the necessary changes to supporting optics, as is well known in the imaging arts.

[0038] With the arrangement of Fig. 3 a, then, the blue color component from spatial light modulator 32b is a two-dimensional image; the red and green color components from spatial light modulators 85r and 85g, respectively, are scanned line images that form a two-dimensional image with sufficient scan rate, as noted above. Moreover, because of reduced eye sensitivity to blue, as noted in the background section above, the two-dimensional blue image from spatial light modulator 32b may even be at a significantly lower resolution (that is, having fewer displayed pixels over the same area) than the corresponding scanned line image from spatial light modulators 85r and 85g. It is important to note that the size and shape of the two-dimensional blue image should be substantially equal to that for the red and green scanned line images. By proper lens design, lens 75 and scan lens 84 could be used to match the size and shape of the red and green scanned line images to that of the two-dimensional blue image. Any residual mismatch in color image sizing could be adjusted in the mapping of electronic image data to spatial light modulators 85r, 85g, and 32b, as necessary.

[0039] Fig. 3b shows an alternate embodiment of display apparatus 10 utilizing a transmissive LCD as an area spatial light modulator 32b in blue color modulation channel 30b. Light from light source 22b is directed through polarizer 34 and blue-pass filter 24b to provide polarized blue light, which is directed through lens 76 to area spatial light modulator 32b. Modulated light from spatial light modulator 32b then travels to polarizing beamsplitter 93, which serves both to select the desired polarization of the blue modulated light and to combine the blue modulated light with red and green modulated light for projection. Red and green color modulation channels 30r and 30g, respectively, in Fig. 3b use linear spatial light modulators 85r and 85g, respectively, in the same manner as described with reference to Fig. 3a.

[0040] Fig. 3c shows an alternative embodiment having a red-green color modulation channel 30rg in which a single electromechanical grating light modulator 85rg serves to alternately modulate both red and green light, in sequential fashion. Red and green illumination are provided by laser sources 20r and 20g that provide, along the same illumination path, a red laser beam and a green laser beam. These different beams could be combined in any of a number of ways well known in the imaging arts, such as using dichroic combiner 94.

[0041] Fig. 3d shows another alternative embodiment of display apparatus 10 in which red-green color modulation channel 30rg uses a dichroic combiner 94 to direct red and green laser light simultaneously to a dual electromechanical grating light modulator 87rg. Dual electromechanical grating light modulator 87rg provides, as a single component, two independently addressable linear arrays of electromechanical grating devices fabricated onto the same substrate. Spatial displacement, such as with laser illumination provided through dichroic combiner 94, or angular displacement could be used to direct the laser light along separate paths for modulation. With the arrangement of Fig. 3d, dual electromechanical grating light modulator 87rg is capable of simultaneously modulating the red and green light, using two separate linear arrays of electromechanical grating devices, for example.

[0042] Fig. 3e shows a four-color embodiment of display apparatus 10. An X-cube 96 is used to combine the modulated light from red and green color modulation channels 30r and 30g with modulated light from a fourth

Color Gamut

[0048] As is noted in the background information given above, one key motivation for using monochromatic laser illumination sources relates to color gamut. Referring back to Fig. 1, it was noted that optimum color gamut is achieved when vertices that define device gamut 202 are on the curve of visible gamut 200. Laser sources provide vertices on the visible gamut 200 curve; other light sources typically provide vertices somewhat back from the visible gamut 200 curve.

[0049] Referring to Fig. 7, there is shown a graph of an improved color gamut 302 using red laser source 20r to provide red vertex 203r, green laser source 20g to provide green vertex 203g, and blue light source 22b to provide blue vertex 203b. Blue light source 22b is preferably an arc lamp having a stable 436 nm wavelength output. As has been described, red and green vertices 203r and 203g are on the periphery of visible gamut 200. Blue vertex 203b, although not directly on this periphery, is very near it as is represented in Fig. 7. Note the considerable enlargement of improved color gamut 302 of the present invention over device gamut 202 available using standard SMPTE phosphors. Thus, while the method of the present invention does not yield the maximum possible color gamut obtainable according to the tri-vertex CIE model, the improvement available using the present invention can be substantial.

[0050] As is noted above with reference to Fig. 3e, expanded color gamut can be obtained by supplementing the conventional red, green, and blue light sources with additional monochromatic sources of other colors. Referring to Fig. 3e, the configuration of display apparatus 10 allows a broadened color gamut, effectively adding a fourth vertex 203bg (see Fig. 7), which may be emitted light in the blue-green region, for example, for defining a larger device gamut 202, as is represented in Fig. 7.

Optical Path Design

[0051] It should be observed that there are differences in handling the different types of modulated light provided by linear and area spatial light modulators. The method of the present invention may require that some compromises be made in order to accommodate both scanned linear and full area imaging. This is in addition to other changes required between color paths to handle light at different wavelengths, for example.

[0052] It has been observed that the modulated image provided by blue color modulation channel 30b is provided as a full image frame, as distinguished from the scanned linear light for red or green color modulation channels 30r and 30g. Moreover, also contrary to convention, the blue image itself may even be at lower resolution than the modulated images provided in red and green color modulation channels 30r and 30g. Because human eye sensitivity to detail is limited in the blue visible region, resolution requirements can be relaxed for blue color modulation channel 30b. With this same consideration, the optical path for modulated light can also be optimized for red and green color imaging where detail (and, to some extent, chromaticity) is more important.

[0053] Figs. 3a, 3b, 3c, 3d, 3e, 3f and 4 show and describe the use of GEMS devices as linear light modulators. However, GLV or other linear devices could alternately be used, provided with the necessary changes to support components, as is well known in the imaging arts.

Optical Component Options

[0054] It should be pointed out that Figs. 2, 3a, 3b, 3c, 3d, 3e, 3f, 4, 5, and 6, show only the components of display apparatus 10 that are used for color modulation. Scanning, projection, and display functions can use components well-known to those skilled in the digital image display arts. Scanning mirror 77 is the simplest of a set of possible devices for scanning the image, one line at a time, toward display surface 90. However, other types of scanning elements could be used, such as a rotating polygon, for example.

[0055] Color combiners 73 typically comprise one or more dichroic surfaces that have been fabricated for reflecting or transmitting light at various wavelengths. Figs. 2 and 5 show X-cubes or X-prisms that operate based on crossed dichroic surfaces, used for color combiner 73. However, other arrangements of color-combining dichroic surfaces may alternatively be used for directing multiple input colors into a single output color path.

[0056] In one embodiment, display surface 90 is a front projection screen; however, a rear-projection screen or other surface could also be used.

[0057] It can be seen that the apparatus and method of the present invention provide a solution to a recognized problem that has heretofore limited the feasibility of economical laser-based projection systems. Moreover, the solution of the present invention provides display apparatus 10 with an expanded color gamut, closely approximating the color gamut that would be achievable with an all-laser illumination system, yet, at a fraction of the cost of such a system. Finally, in contradistinction to conventional approaches for digital imaging, the method and apparatus of the present invention employ different types of spatial light modulators in different color channels of a single projection system, with the added option of using lower resolution in the blue color channel where detail is less perceptible.

[0058] Specific components in red, green, and blue color modulation channels 30r, 30g, and 30b, respectively, can be varied to suit the type of image modulation being performed. More than 3 or 4 color channels could be employed, such as where additional colors would enhance the available color gamut.

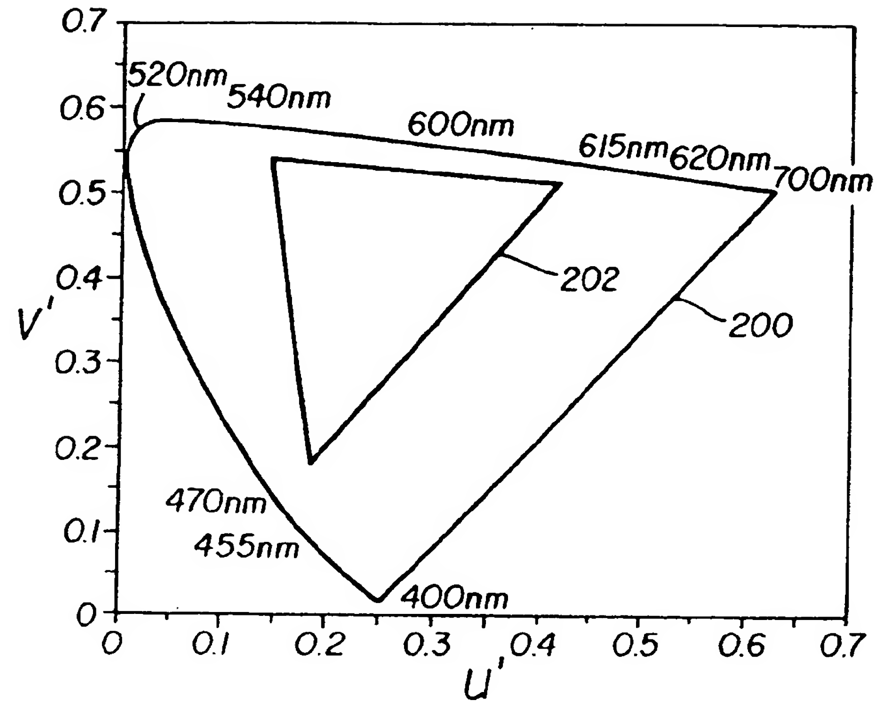


FIG. 1
(Prior Art)

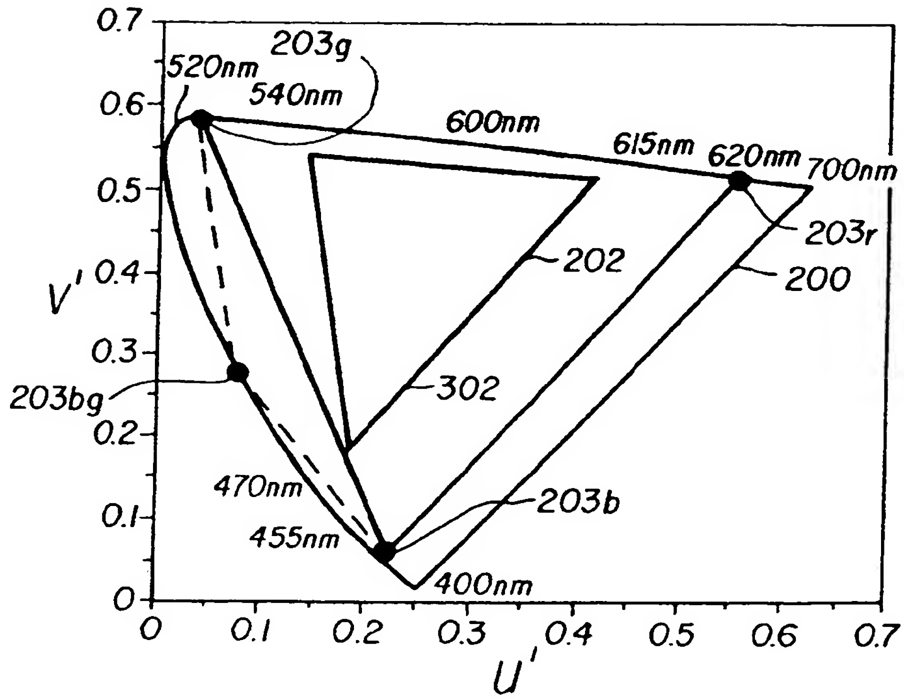
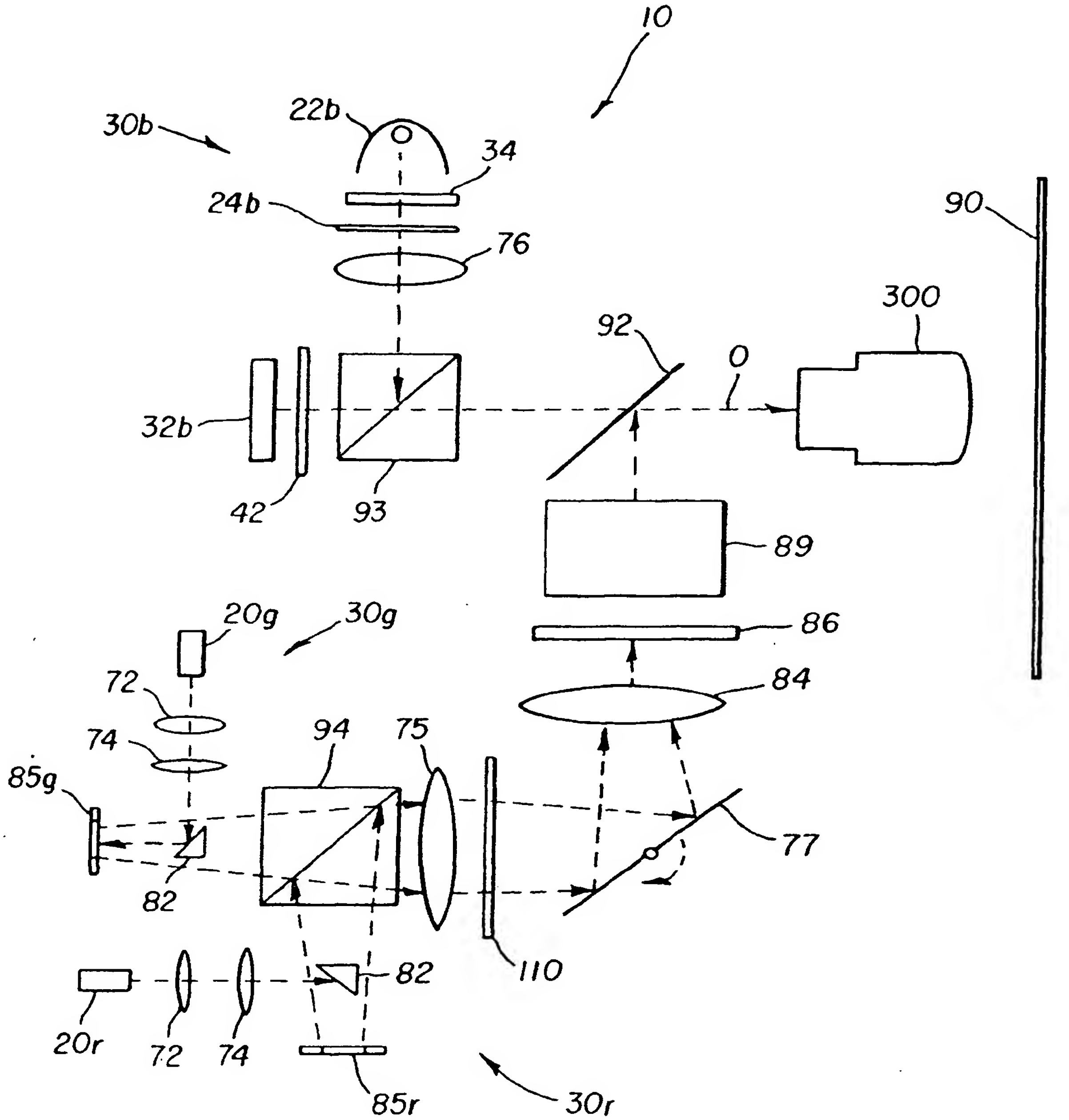


FIG. 7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77
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20r
72
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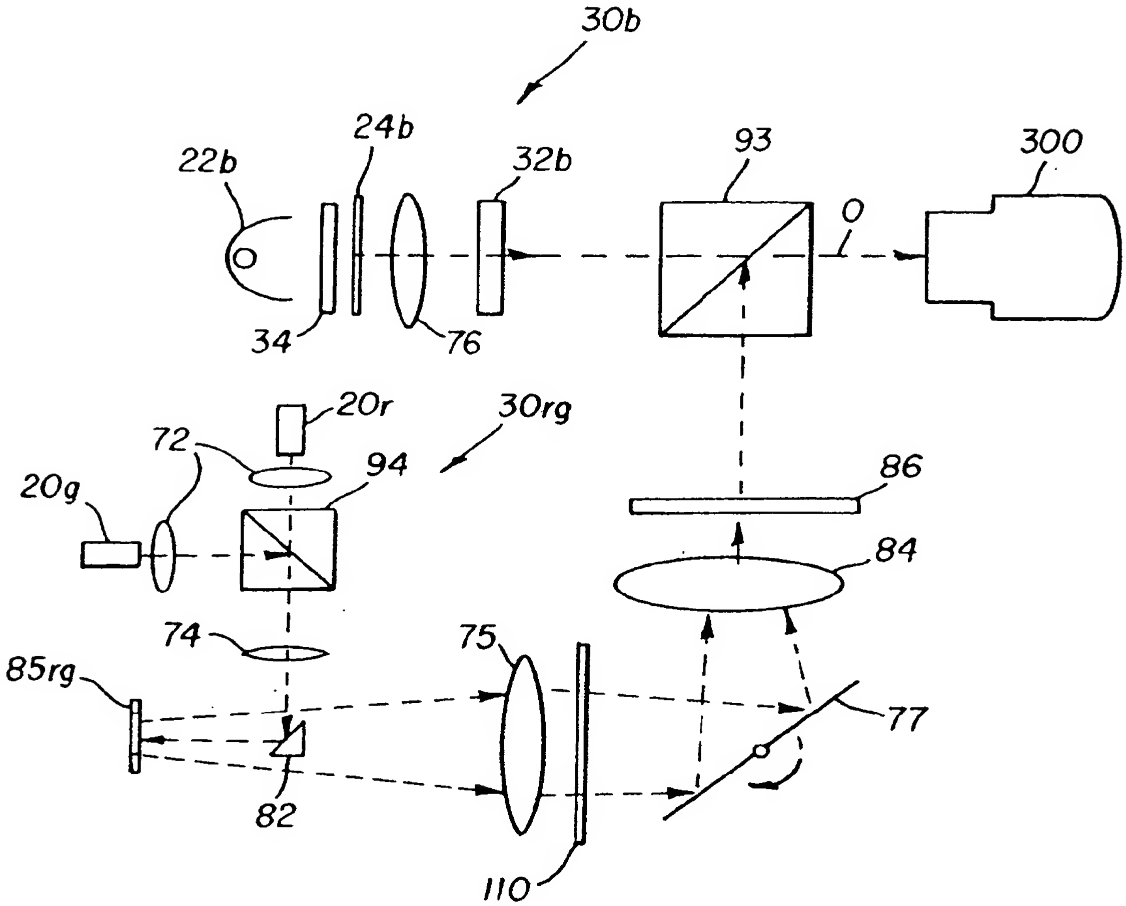
85r
30r

FIG. 3a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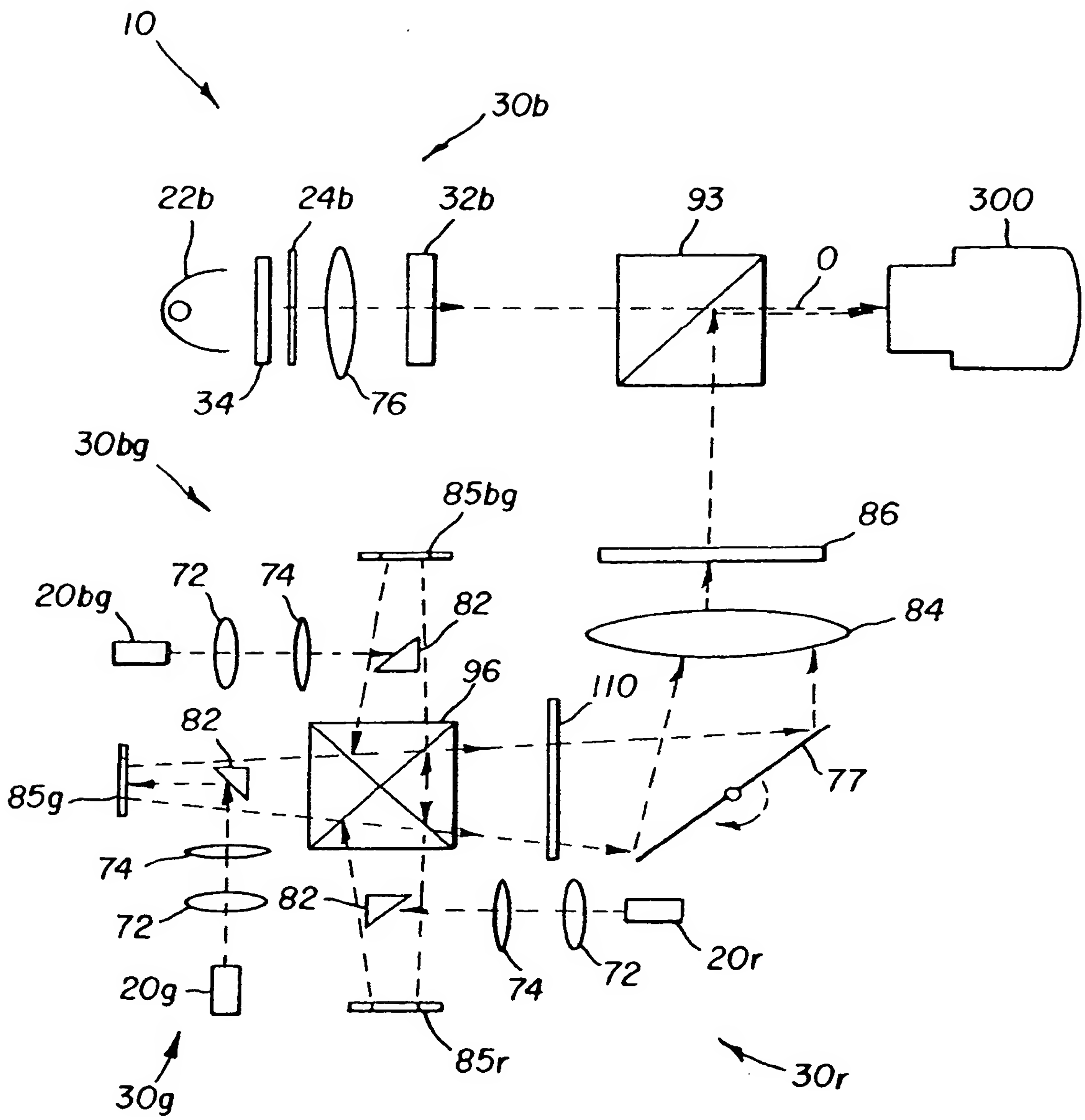
82
110

FIG. 3c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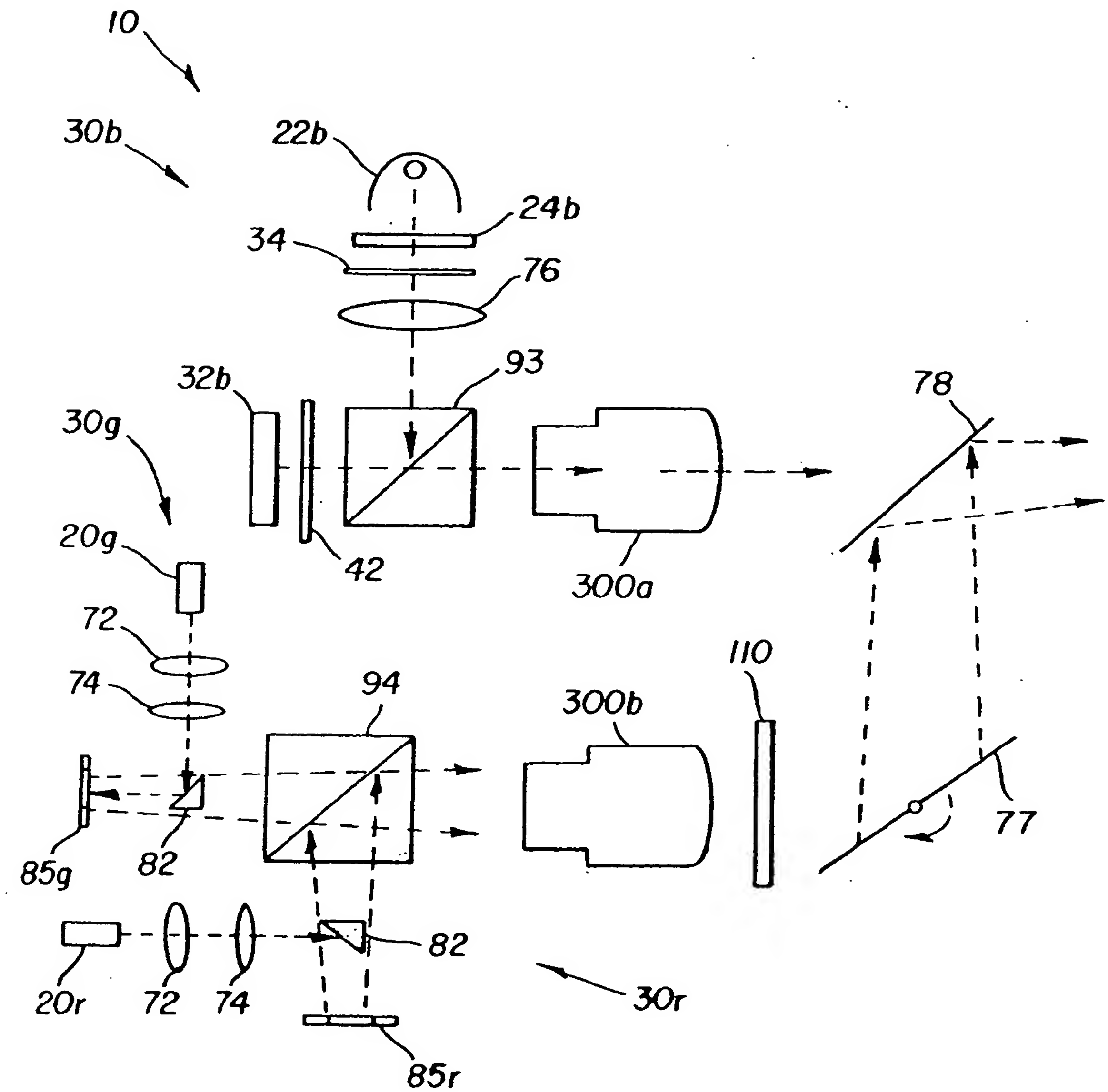
85r
30g
30r

FIG. 3e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20r
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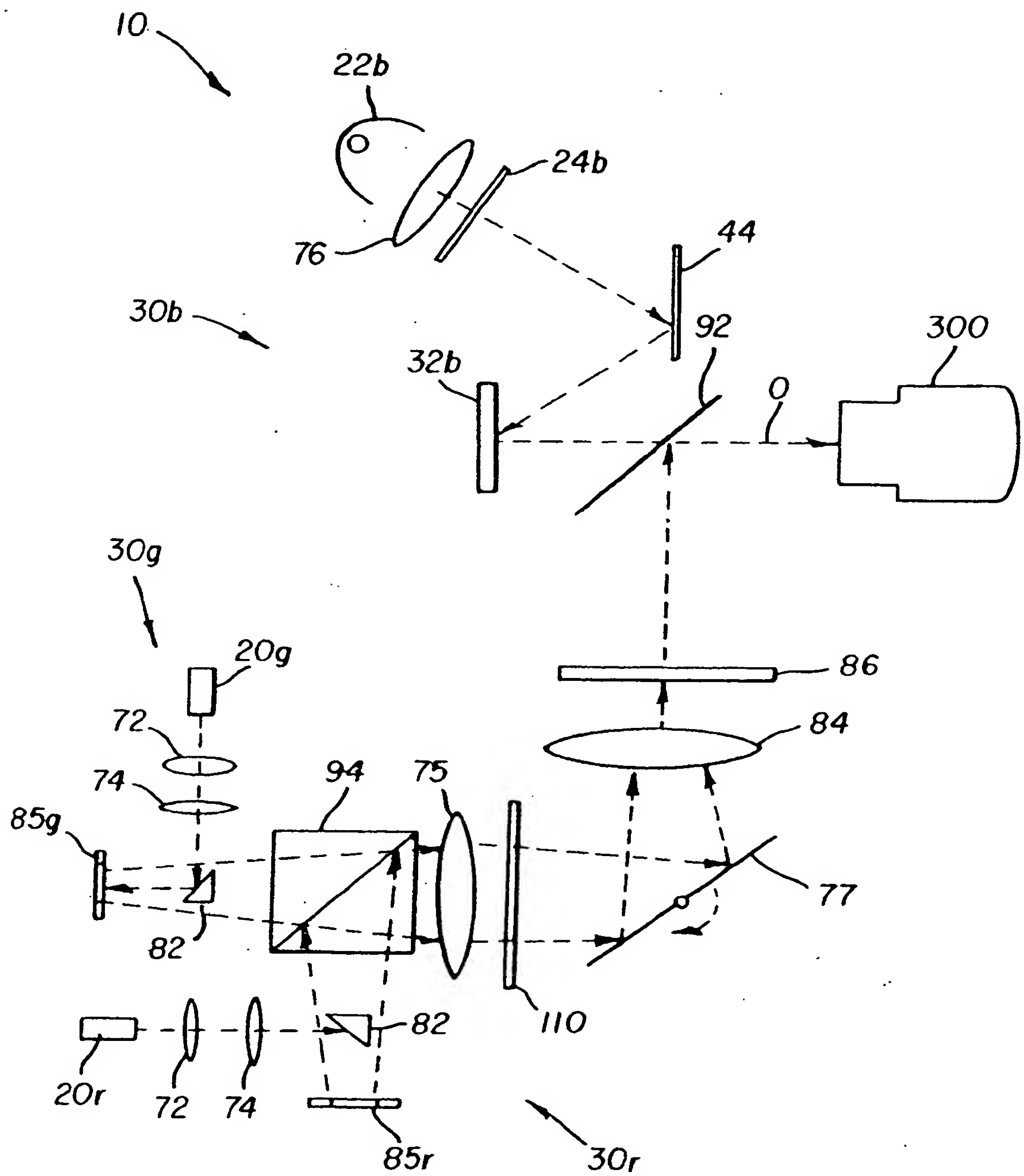
74
30r
85r

FIG. 4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20r
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74
85r
30r

FIG. 6

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 03 07 8440

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